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Role of Electrostatic Interactions in the Retention of Pharmaceutically Active Contaminants by a Loose Nanofiltration Membrane

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Abstract

The role of electrostatic interactions in the separation of pharmaceuticals by a loose nanofiltration (NF) membrane was examined. While retention of the non-ionizable pharmaceutical carbamazepine was relatively independent of the solution chemistry, retention of the ionizable pharmaceuticals sulfamethoxazole and ibuprofen was strongly influenced by the solution pH and ionic strength. This finding is consistent with previous results investigating the effects of solution pH and ionic strength on the retention of proteins and organic acids. Pharmaceutical retention increases dramatically as the compound transforms from a neutral to a negatively charged species when the solution pH increases above its pK_a value. In contrast, solution ionic strength suppresses the double layer or the Debye screening length and therefore reduces the effectiveness of electrostatic interaction as a major retention mechanism by the loose NF. However, because of the formation of a hydrated layer around the charged functional groups of the pharmaceuticals and the fact that at a sufficiently high ionic strength the Debye length approaches a relatively constant value, this reduction in retention is relatively small. As a result, even at comparatively elevated ionic strengths, retention of the negatively charged sulfamethoxazole and ibuprofen by the loose NF membrane is considerably high.

Keywords: nanofiltration, pharmaceutically active compounds, charge repulsion, retention mechanisms

1 Introduction

In recent years, there has been considerable research effort focusing on removing specific individual contaminants instead of the surrogate and often ill-defined water quality indicators. This paradigm shift is mainly driven by stricter environmental regulations and legislation, greater need to utilize non-traditional water resources including water reclamation and water recycling. Further, partial removal of such compounds in water and wastewater treatment, and particularly the availability of advanced treatment technologies such as advanced oxidation, carbon adsorption, and membrane filtration as well as hybrid processes have contributed to a greater interest in understanding removal mechanisms. The centre of attention amongst such contaminants is a group known as pharmaceutically active compounds (PhACs), which has been a major concern due to their widespread occurrence of sub microgram per liter concentrations in the aquatic environment. Most pharmaceuticals are not fully assimilated and hence excreted after administration to humans or animals. They can resist biodegradation during conventional wastewater treatment processes to a considerable extent, depending on their

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physicochemical characteristics. Several pharmaceuticals such as carbamazepine are highly persistent and are not removed at all by wastewater treatment plants (WWTPs) [1, 2]. In other cases, the high degradation rate of the pharmaceuticals can be virtually offset by their continuous introduction into the environment.

Research to date has clearly indicated the abundance of PhACs in sub microgram per liter concentrations in secondary treated effluent, surface water, ground water, and in extreme cases even in drinking water [3-5]. Because pharmaceuticals are designed to be biologically active, they have the potential to induce chronic sublethal effects on living organisms and any of such adverse health effects can instill serious consequences. It is therefore essential to prevent contaminants such as PhACs from entering the aquatic environment [4], and particularly so prior to potable water recycling.

Solute separation in a nanoporous membrane filtration process is driven mostly by size exclusion (also known as steric interactions) and electrostatic interactions. The former is often described by the hydrodynamic model where porous membranes are presented as bundles of straight, narrow, cylindrical pores and steric interactions are taken into account to correct for the hindered convection and diffusion of uncharged solute within the membrane pores [6]. Using the extended Nernst-Planck equation to include the Donnan or dielectric exclusion due to interactions between the membrane charged surface and the charged solute, several models has been developed to describe the latter. Amongst the early versions of these, the space charge model proposed by Wang et al. [7] assumed ions as point charges and focused almost exclusively on the electrostatic interactions between solute and the membrane charged surface. Recently, a more rigorous description of the dielectric exclusion behavior has also been developed for both monovalent and multivalent salts by Bowen and Welfoot [8]. Because mineral salts were used as model solutes in most of these studies, a knowledge gap remains with respect to electrostatic interactions between charged organic compounds, particularly trace organics, and the membrane charged surface. Over the last few decades, due to commercial interest in several organic compounds such as proteins and lactate salts, contributions of electrostatic interactions to the transport of these solutes in porous membrane systems have also been the subject of extended research. Several studies have shown, for example, that protein transport is a function of the membrane surface charge characteristics and protein retention increases significantly under conditions where the membrane and protein have the same charge due to increased electrostatic repulsion. Furthermore, there is substantial experimental evidence that these electrostatic interactions between proteins and the membrane surface are dependent of the solution chemistry, such as pH and ionic strength. For example, Burns and

Zydney [9, 10] and Nakao *et al.* [11] evaluated the effect of solution pH on the passage of proteins through ultrafiltration membranes and found that the maximum passage was typically attained near the protein isoelectric point where the protein has no net electrical charge. Millesime *et al.* [12] reported a significant decrease in the retention of bovine serum albumin and lysozyme from as high as 100% to only 35% and 10%, respectively, as the solution ionic strength increased to 1 M by adding NaCl to the feed solution. This is consistent with the results reported earlier by Pujar and Zydney [13]. Both groups attributed this behavior to the decrease in electrostatic repulsion at high ionic strength.

To date, most theoretical analyses on the effects of electrostatic interactions on organic solute transport in membrane filtration were carried out with proteins [9-11, 13] and to a lesser extent lactate salts as model solutes [14, 15]. There is currently a lack of information with respect to the influence of solution chemistry on the separation process of charged pharmaceuticals, particularly by loose NF membranes. Although the transport behavior of small organic compounds may follow some of the trends observed for that of proteins, there are several fundamental differences in their physicochemical characteristics. First, proteins are relatively large macromolecules. While a protein molecule can contain multiple charged moieties, small organic compounds such as pharmaceuticals typically consist of a single charged functional group. Consequently, the conformation and size of a macromolecule can vary considerably due to intra-molecular electrostatic interactions between its charged groups. On the other hand, given the much smaller size of pharmaceuticals, the contribution of the hydrated layer may play a role in their passage through the membrane pores. It is also noteworthy that studies investigating the separation of proteins and lactate salts often employed a very high background electrolyte concentration of up to 1M, typical to that of an industrial application rather than the water recycling context.

Given the significant role that membrane filtration has taken on in the water industry [16], especially for water recycling, the use of nanofiltration (NF) membranes for the removal of trace organics has been intensively investigated [17-21]. None of these studies, however, have examined the role of electrostatic interactions in the removal of PhACs by loose NF membranes. The objective of this study is to examine the role of electrostatic interactions in the removal of pharmaceuticals by such a loose polymeric NF membrane. Both the membrane and the pharmaceuticals were characterized in detail. The membrane retention behavior was related to the physicochemical properties of the pharmaceuticals and the membranes as well as to the solution chemistry. Variation is solution chemistry involved pH,

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ionic strength, and presence of divalent cations. On the basis of the results, the role of electrostatic interactions in the nanofiltration of the selected pharmaceuticals was elucidated and discussed.

2 Materials and Methods

2.1 Nanofiltration membrane

Flat sheet samples of a loose thin film composite NF membrane — denoted TFC-SR2 (Koch Membrane Systems, San Diego, CA) — were used in this investigation. The membrane consists of a thin polyamide skin layer on top of a microporous polysulfone support. This membrane was selected because of its low salt and high organic matter retention which makes it a very desirable membrane if desalination or hardness removal is not required. It was received as flat sheet sample and was stored dry at 4 ^{o}C.

2.2 Pharmaceutically active contaminants (PhACs)

Three common pharmaceuticals — sulfamethoxazole, carbamazepine, and ibuprofen — representing three different drug categories, were selected for this study. **Figure 1** depicts the structures of these compounds. The compounds were purchased from Sigma-Aldrich (Saint Louis, MO). The purity of these chemicals was reported to be 99 % or higher. Sulfamethoxazole is an important member of the sulfonamide antibacterial category and is probably the most frequently used antibiotic; carbamazepine is one of the most widely used anti-epileptic drugs; and ibuprofen is a common anti-inflammatory agent. Because they belong to three different drug categories, these pharmaceuticals have quite distinctive functional groups (**Figure 1**). The pharmaceuticals were first dissolved in pure methanol to make up stock solutions of 1 g/L. The stock solutions were stored at < 4 ^{o}C and were used within 1 month.

[**Figure 1**]

2.3 Cross flow membrane filtration system and filtration protocol

A laboratory-scale membrane filtration unit with a rectangular stainless steel crossflow cell (effective membrane area of 40 cm^2 and a channel height of 2 mm) was used for the experiments. The temperature of the test solution was controlled using a chiller/heater (Neslab RTE 7) equipped with a stainless steel heat exchanger coil. Permeate flow was measured by a digital flow meter (Optiflow 1000, Agilent Technologies, Palo Alto, CA) connected to a PC, and the cross flow/feed flow was monitored with a rotameter.

Prior to each experiment, the membrane was stabilized at 12 bar using DI water for approximately 16 hours until there was no further variation in permeate flux. The feed reservoir temperature was kept constant at 20 ± 0.1 ^{o}C throughout the experiment. Both permeate and retentate were recirculated back to the feed reservoir. In all filtration experiments, the background electrolyte solution contained 20 mM NaCl and 1 mM $NaHCO_3$, and, unless otherwise stated, the pH was kept at 8.

Prior to experimenting with pharmaceuticals, the DI water used for membrane compaction was replaced with 7 liters of fresh DI water. The cross flow velocity and permeate flux were adjusted to 30.4 cm/s and 15 μm/s (54 $Lm^{-2}h^{-1}$), respectively. Pharmaceuticals were then spiked into the feed reservoir to make up a concentration of 500 μg/L. Approximately 1.5 mL of feed and permeate samples were taken for analysis at specified time intervals.

For experiments with variable pH, the solution was adjusted to pH 10.5 by addition of a proper volume of 1 M NaOH. The pH was then incrementally dropped to 3.5 using stepwise additions 1 M HCl. For experiments with variable electrolyte concentration, the initial solution contained 1 mM $NaHCO_3$ and the pH was kept at 8. NaCl solution (1 M) and $CaCl_2$ (0.2 M) were then added to the feed reservoir to incrementally increase the electrolyte concentration as required. The system was equilibrated for 1 hour prior to sample collection at each pH or electrolyte concentration value. Observed retention is defined as $R = 100\times(1 - C_P/C_F)$, where C_P and C_F are the permeate and the feed concentrations, respectively.

2.4 Analytical methods

A Shimadzu HPLC system (Shimadzu, Kyoto, Japan) equipped with a Supelco Drug Discovery C-18 column and a UV detector was used to analyze pharmaceutical concentration in the feed and permeate samples. Detection wavelengths for sulfamethoxazole and carbamazepine were set at 280 nm, and for ibuprofen at 225 nm. DI water (buffered with 0.025 M KH_2PO_4) and acetonitrile were used as the mobile phase. The mobile phase was delivered at a constant flow rate of 1 mL/min with a gradient set in accordance with the chromatographic behavior of the respective analytes. Analysis was carried out immediately following the nanofiltration experiments.

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3 Results and discussion

3.1 Membrane characteristics

Characteristics of the TFC-SR2 membrane have been previously described. It was reported to be relatively hydrophilic with contact angle of approximately 20^o measured using the sessile drop technique [22]. The membrane retains a small percentage of calcium while sodium retention is virtually negligible [22]. Pore size measurement following the procedure described in our previous publication [23] indicates that this membrane has a relatively open pore size, with an average pore radius determined of 0.64 nm. Despite being a loose NF membrane, the TFC-SR2 membrane has a relatively high natural organic matter removal of 70-85% [24], which is the characteristic of the SR series. High flux and high salt passage in combination with a moderate to high organic matter removal make the TFC-SR2 membrane particularly attractive for water recycling as well as surface water treatment. In such applications, salt removal is unnecessary and often undesirable due to the energy loss with the buildup of osmotic pressure and the production of a brine that requires further treatment and disposal.

As expected, sodium chloride retention (estimated by conductivity measurements) by the TFC-SR2 membrane is very small, yet the membrane attains a considerable negative charge at pH values above pH 5 (**Figure 2**). Below pH 5, the membrane zeta potential varies sharply as a function of pH, from slightly positive at pH 2.5 to −10 mV at pH 5. This is due to the deprotonation or protonation of the membrane functional moieties, which in this case consist of predominantly carboxylic and amine groups [25]. It is noteworthy that the membrane zeta potential can provide a good indicative parameter to assess the membrane surface charge density [25, 26]. The membrane zeta potential or charge density does have a small but discernible influence on the retention of sodium chloride (**Figure 2**). This observation suggests that electrostatic interaction plays a small role in the separation process of ionic species by the TFC-SR2 membrane. Retention is smallest near the isoelectric point of the membrane. Due to the relatively large pore radius of the membrane (0.64 nm) with regard to the hydrated radii of the chloride or sodium ions, which have been reported to be 0.20 and 0.18 nm [27], respectively, the effect is relatively small. However, as will be discussed in a later section, electrostatic interactions can contribute substantially to the retention of charged organic molecules.

[**Figure 2**]

3.2 Physicochemical properties of the selected PhACs

Because of the differences in functional groups, the three pharmaceuticals selected for this study exhibit markedly different physicochemical properties (**Table 1**). While carbamazepine is uncharged at common pH conditions typical of natural water or wastewater, both ibuprofen and sulfamethoxazole exhibit a wide variation in speciation (or charge) and physicochemical properties. At pH below its pK_a value (pH 4.9), ibuprofen is a neutral species. Above this pK_a value, ibuprofen attains a negative charge. Speciation of sulfamethoxazole as a function of pH has been described elsewhere [28]. This pharmaceutical can exist in positive, neutral, as well as negative forms as it possesses two ionizable amine groups. At pH above the compound's second pK_a value (pH 5.7), sulfamethoxazole exists predominantly as a negatively charged species. It is noteworthy that values of the hydrophobicity presented in **Table 1** are assumed to represent characteristics of the compounds in their neutral form. Data for other pH values can be obtained by considering the effective partition coefficient (commonly known as logD) for the dissociative systems and can be found in databases such as SciFinder. Variations in charge and other physicochemical properties as a function of pH may have important implications for the separation mechanisms of these pharmaceuticals.

[Table 1**]**

3.3 Steric hindrance and electrostatic interactions

Figure 3 presents the concentration of sulfamethoxazole, carbamazepine, and ibuprofen in both permeate and feed solutions as a function of time during filtration with the TFC-SR2 membrane at pH 4.0. Because of their low hydrophobicity, both sulfamethoxazole and carbamazepine do not adsorb to the membrane at these experimental conditions, which is evident from their constant feed concentrations for the duration of the experiments. Interestingly, despite the fact that the TFC-SR2 has a relatively hydrophilic surface, ibuprofen adsorbs considerably to this membrane, which manifests itself as decreasing feed concentration (from 500 to about 300 µg/L) until equilibrium is reached (**Figure 3**). In its neutral form, ibuprofen is a highly hydrophobic compound as reflected by its high logK_{ow} value (**Table 1**) and this observed adsorption can probably be attributed to hydrophobic interactions between ibuprofen and hydrophobic domains within the membrane polymer matrix. It is noteworthy that the molecular size of ibuprofen (**Table 1**) is considerably smaller than the average pore size of the TFC-SR2 membrane, and therefore, adsorption is not confined to the membrane surface and hence can take place throughout the polymer structure. As can be seen in **Figure 3**, this adsorption

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initially appears as a low permeate concentration (and hence high retention) while equilibrium is reached after about 2.5 hours of filtration.

[**Figure 3**]

At equilibrium when no further adsorption is observed, ibuprofen retention of approximately 35% can be inferred from **Figure 3**. This is significantly higher than the retentions of both sulfamethoxazole and carbamazepine, which are practically negligible despite the fact that these pharmaceuticals have about the same molecular size (**Table 1**). As discussed previously, at this experimental condition of pH 4, sulfamethoxazole and carbamazepine exist in their neutral form while 10% of ibuprofen still carries a negative charge. Consequently, this can be a major factor for the difference in retention between ibuprofen and the other two pharmaceuticals. Further reason for this can be due to the adsorption of the neutral ibuprofen onto the membrane and pore surfaces, leading to a higher observed retention, some of which may also be related to pore size reduction. Similar observation has also been made when the effects of adsorption on protein retention by ultrafiltration membranes was evaluated [29]. In addition, a sufficiently high dipole moment (above 3 D) can induce an electrostatic attraction between the membrane surface and the polar centers of the molecule [30]. Because the dipole moment of both sulfamethoxazole and carbamazepine is quite high (**Table 1**), the molecules tend to approach the membrane pore head on which results in a lower retention [30].

At pH 8, where both sulfamethoxazole and ibuprofen are negatively charged (carbamazepine remains neutral and hence has not been investigated), electrostatic attraction induced by the compound's polarity can be overcome by the electrostatic repulsion (**Figure 4**). Due to electrostatic repulsion (or charge exclusion), sulfamethoxazole is retained to some extent while the retention of ibuprofen is considerably higher than that at pH 4. It is noteworthy that at this pH, ibuprofen does not adsorb to the membrane as indicated by the constant feed and permeate concentrations throughout the experiment.

[**Figure 4**]

The effect of speciation (in other words the variation in charge of a species as a function of pH) on retention is further illustrated in **Figure 5**. Because carbamazepine is neutral at all pH values in examined here, carbamazepine retention is constant and independent of solution pH (and membrane charge). In contrast, retention of both sulfamethoxazole and ibuprofen varies markedly, resembling their speciation curves as a function of pH, with the exception of high ibuprofen retention at low pH

due to adsorption. This is consistent with several other studies where the nanofiltration of lactic or amino acids was investigated [15, 31-33].

[**Figure 5**]

The presented results indicate a distinctive difference between the retention behaviors of ionizable organic compounds and inorganic salts such as NaCl. As reported in an earlier section, sodium chloride retention was small and relatively constant over a wide pH range from 2 to 8 (**Figure 2**). Again, one can speculate that the retention behavior is attributed to the relative size difference between the solute and the membrane pore. Sulfamethoxazole and ibuprofen are considerably larger than the chloride ion (**Table 1**).

It is also interesting to point out that ibuprofen retention is consistently higher than that of sulfamethoxazole. This can possibly be explained by the fact that ibuprofen is an organic acid. Therefore, when dissociated, the negative ibuprofen species has a higher charge density than that of sulfamethoxazole, which is deprotonated via the dissociation of an amine group. Such a higher charge density would result in not only an increase in charge repulsion, but also a larger molecule hydrated size.

3.4 Influence of background electrolyte: Monovalent Salt

Solution ionic strength is directly related to the Debye length or the double layer thickness of the charged solutes and at the membrane surface, which in turn governs electrostatic interaction in NF processes. It is hence expected to influence the separation of charged solutes by NF membranes to some extent. Indeed, experimental data at pH 8 for the two charged compounds, presented in **Figure 6**, appear to strongly support this hypothesis. As ionic strength increases (represented by an increase in sodium chloride concentration), the Debye length becomes smaller. In other words, electrostatic interaction between the membrane and charged molecules is screened resulting in lower electrostatic repulsion and hence reduced retention. However, it should be noted that the Debye length is a characteristic length for the range of electrostatic interaction and does not represent the actual dimension of a charged particle or surface. One can imagine the Debye length as an extension of a membrane pore (or more precisely a surface functional group) and of a molecule (or its charged functional group). One can further picture that this Debye length 'diminishes' the effective size of a pore or increases the effective size of a molecule. A qualitative picture of such an effect is shown in **Figure 7**. If dimensions are of the right proportions, that is if Debye length is of the same order of

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magnitude as the size difference between molecule and pore, then such a variation may be a determining factor in the retention of a charged molecule by a charged membrane. It is noted that Figure 7 presents a conceptual model and does not show the Debye length overlap.

[**Figure 6**]

[**Figure 7**]

It can also be confirmed that this influence of ionic strength on retention is absent when the solute is neutral at pH 4 (**Figure 8**). Consequently, the molecule retention is constant as sodium chloride concentration in the feed increase up to 70 mM (or 4095 mg/L). While an increase in salt concentration can occur for varying feed waters, for most nanofiltration and reverse osmosis membranes that retain salt such an increase in salt concentration also occurs in the polarized layer near the membrane surface.

[**Figure 8**]

3.5 Influence of background electrolyte: Divalent Salts

As expected, the influence of $CaCl_2$ concentration on the retention of negatively charged pharmaceuticals is more dramatic (**Figure 9**). Calcium is a divalent ion and thus is more effective in screening the molecule and membrane charge. Furthermore, calcium can also reduce the membrane charge because of its binding capacity to the membrane surface functional groups. As calcium chloride concentration increases to 8 mM, retention of the negatively charged pharmaceuticals appears to reach a plateau value while a concentration of 80 mM of NaCl is necessary for sulfamethoxazole and ibuprofen retention to reach a relatively constant value (**Figure 6**).

[**Figure 9**]

In both cases, this plateau retention value is significantly higher than the retention of neutral sulfamethoxazole and ibuprofen (**Figures 3** and **5**). This is possibly due to a limitation in the compressibility of the double layer at increasing ionic strength. As demonstrated in **Figure 7**, the Debye length decreases as the ionic strength or salt concentration increases following an exponential decay pattern. At concentration above 80 mM for NaCl, an increase in ionic strength only results in a small incremental decrease in the Debye length. Similar conclusion can also be inferred for $CaCl_2$,

although in this case, $CaCl_2$ reduces the Debye length more effectively and therefore above 8 mM of $CaCl_2$, the Debye length decrease is negligible as $CaCl_2$ concentration is further increased.

A further consideration is the formation of a hydrated layer around the negatively charged moiety of the pharmaceuticals and the membrane functional groups. While very little is known about the hydration of polymers and organic molecules, this effect possibly results in a considerable increase in their apparent size. For example, the thickness of a monolayer of water molecules is approximately 0.1 nm. Although the hydration energy or hydrated radius of the negatively charged pharmaceuticals investigated here are not available in the literature, it appears that the hydration energy of the anions is stronger than that of the cations [26]. Consequently, hydration may also be a considerable factor contributing to the difference in retention at a sufficiently high ionic strength between neutral and negatively charged pharmaceuticals as observed in **Figures 8** and **9**.

4 Conclusion

Results reported here indicate that retention of the ionizable pharmaceuticals at the low concentrations examined is strongly influenced by solution pH and ionic strength. These results are consistent with previous studies on retention of proteins and organic acids such as lactic acid. Solution pH governs the speciation (or charge) behavior of the compound and therefore the retention mechanisms. Pharmaceutical retention increases dramatically as the compound transforms from a neutral to a negatively charged species as solution pH increases above its pK_a value. Ionic strength screens the molecule and membrane charges and therefore reduces the effectiveness of electrostatic repulsion as a major retention mechanism by the loose NF membrane. However, such a reduction is relatively small and at a comparatively high ionic strength, retention of the negatively charged sulfamethoxazole and ibuprofen by the loose NF membrane remains considerably high at 50-85%. This is probably attributed to the incompressibility of the Debye length at a sufficiently high ionic strength (about 80 mM) and the formation of a hydrated layer surround the negatively charged moieties of the pharmaceuticals.

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Table 1. Physicochemical Properties of Pharmaceuticals [a] [34], [b] [35], [c] [36], [d] Calculated by the Wilke-Chang and the Stokes-Einstein equations [37]. These values present the size of the neutral compounds, [e] estimated using HyperChem 7.0 [38], [f] [39], [g] [40].

Pharmaceutical	MW (g/mol)	pK_a	Stokes radius (nm)	Log K_{ow}	Dipole Moment (D)
Sulfamethoxazole	253.3	pK_{a1} = 1.7 [a] pK_{a2} = 5.6 [a], 5.7 [b]	0.38 [d]	0.89 [c]	5.4 [e]
Carbamazepine	236.3	2.3 [c]	0.37 [d]	2.45 [c]	3.6 [e]
Ibuprofen	206.3	4.4 [e] - 4.9 [c]	0.34 [d]	3.5 [c], 4.13 [f]	1.8 [g]

Nghiem, D.L. ; Schäfer, A.I. ; Elimelech, M. (2006) Role of Electrostatic Interactions in the Retention of Pharmaceutically Active Contaminants by a Loose Nanofiltration Membrane, Journal of Membrane Science, 286, 1-2, 52-59
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FIGURE CAPTIONS

Figure 1. Chemical structures of the three pharmaceuticals used in this study.

Figure 2. Zeta potential of the TFC-SR2 membrane (in a background electrolyte solution containing 20 mM NaCl and 1 mM $NaHCO_3$) and conductivity retention (feed solution contained 20 mM NaCl and 1 mM $NaHCO_3$) by the TFC-SR2 membrane as a function of pH.

Figure 3. Feed and permeate concentration of the uncharged (a) sulfamethoxazole, (b) carbamazepine, and (c) ibuprofen species as a function of filtration time for the TFC-SR2 membrane. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 20 mM NaCl and 1 mM $NaHCO_3$. Other experimental conditions were as follows: cross flow velocity = 30.4 cm/s, permeate flux = 15 μm/s (54 $Lm^{-1}h^{-1}$), pH = 4, and temperature = 20 ^oC.

Figure 4. Feed and permeate concentration of the negatively charged (a) sulfamethoxazole and (c) ibuprofen species as a function of filtration time for the TFC-SR2 membrane. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 20 mM NaCl and 1 mM $NaHCO_3$. Other experimental conditions were as follows: cross flow velocity = 30.4 cm/s, permeate flux = 15 μm/s (54 $Lm^{-1}h^{-1}$), pH = 8, and temperature = 20 ^oC.

Figure 5. Retention of sulfamethoxazole, carbamazepine, and ibuprofen by the TFC-SR2 as a function of the solution pH. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 20 mM NaCl and 1 mM $NaHCO_3$. Other experimental conditions were as follows: cross flow velocity = 30.4 cm/s, permeate flux = 15 μm/s (54 $Lm^{-1}h^{-1}$), and temperature = 20 ^oC.

Figure 6. Retention of anionic sulfamethoxazole and ibuprofen by the TFC-SR2 as a function of the solution NaCl concentration. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 1 mM $NaHCO_3$ and varied concentration of NaCl. Other experimental conditions were as follows: cross flow velocity = 30.4 cm/s, permeate flux = 15 μm/s (54 $Lm^{-1}h^{-1}$), pH = 8, and temperature = 20 ^oC.

Figure 7. The calculated Debye length as a function of the solution NaCl concentration and a schematic description of the interplay between the Debye length of a charged molecule and an

idealized membrane pore (a) relatively high retention at low ionic strength and (b) lower retention at high ionic strength.

Figure 8. Retention of the uncharged sulfamethoxazole and carbamazepine species by the TFC-SR2 as a function of the solution NaCl concentration. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 1 mM $NaHCO_3$ and varied concentration of NaCl. Other experimental conditions were as follows: cross flow velocity = 30.4 cm/s, permeate flux = 15 μm/s (54 $Lm^{-1}h^{-1}$), pH = 4, and temperature = 20 ^oC.

Figure 9. Retention of anionic sulfamethoxazole and ibuprofen by the TFC-SR2 as a function of the solution $CaCl_2$ concentration. The feed solution contained 500 μg/L of the corresponding pharmaceuticals in a background electrolyte solution containing 1 mM $NaHCO_3$ and varied concentration of $CaCl_2$. Other experimental conditions were as in Fig. 6.

Nghiem, D.L. ; Schäfer, A.I. ; Elimelech, M. (2006) Role of Electrostatic Interactions in the Retention of Pharmaceutically Active Contaminants by a Loose Nanofiltration Membrane, Journal of Membrane Science, 286, 1-2, 52-59
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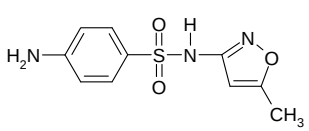
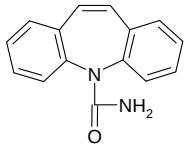
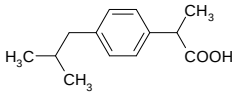


Sulfamethoxazole



Carbamazepine



Ibuprofen

Figure 1

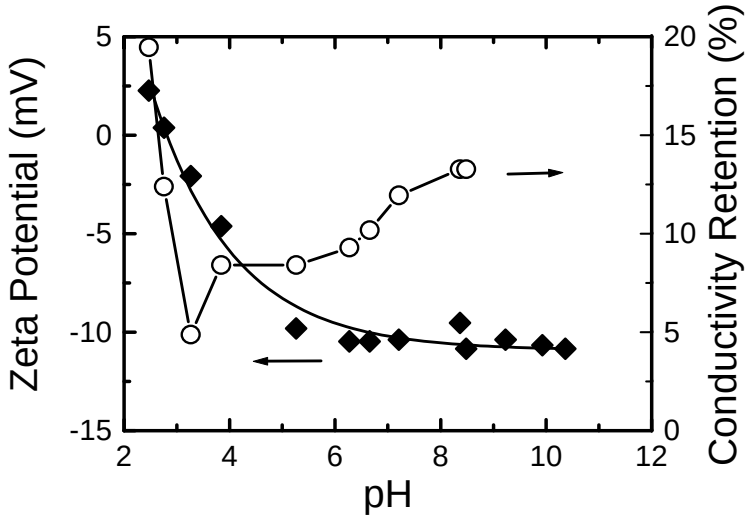


Figure 2

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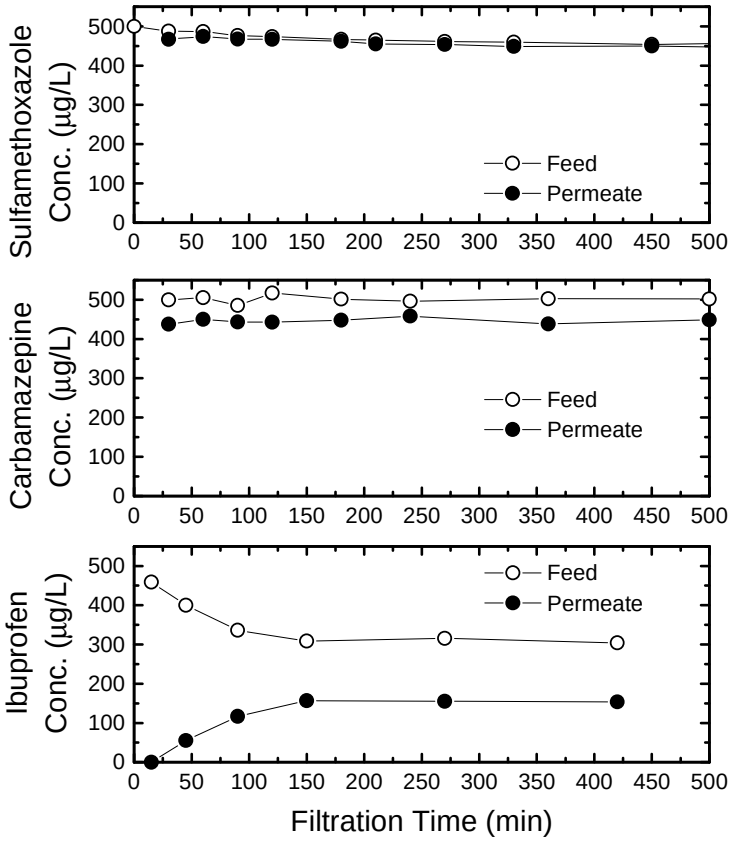

Figure 3

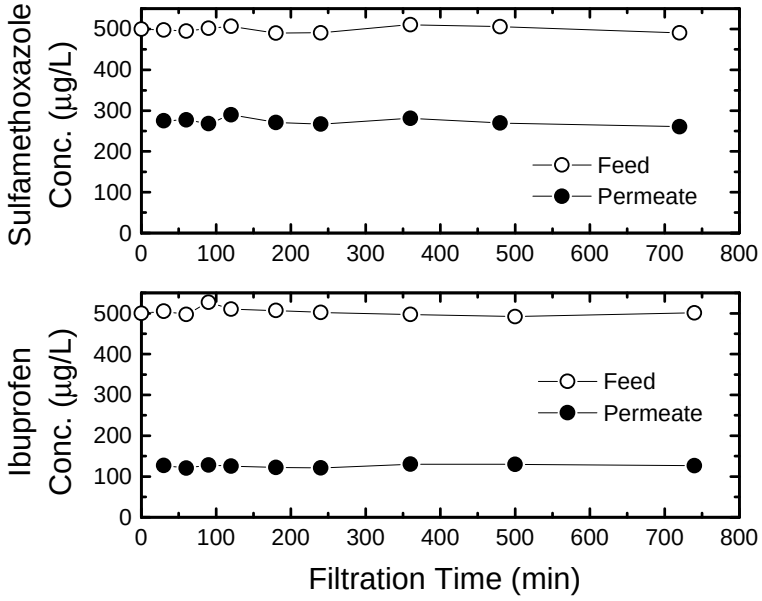

Figure 4

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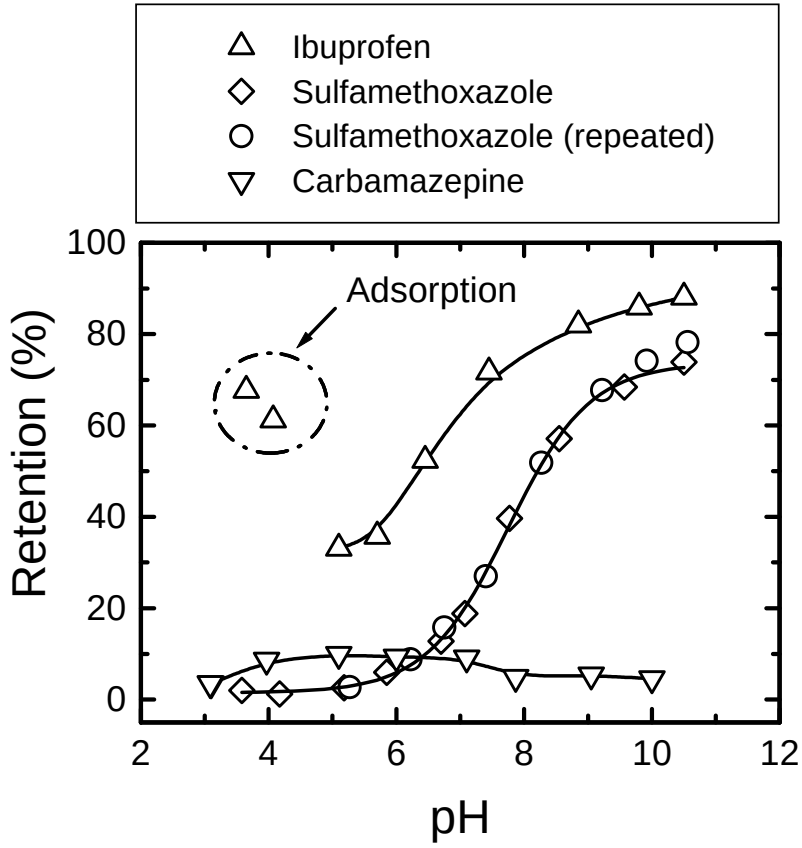

Figure 5

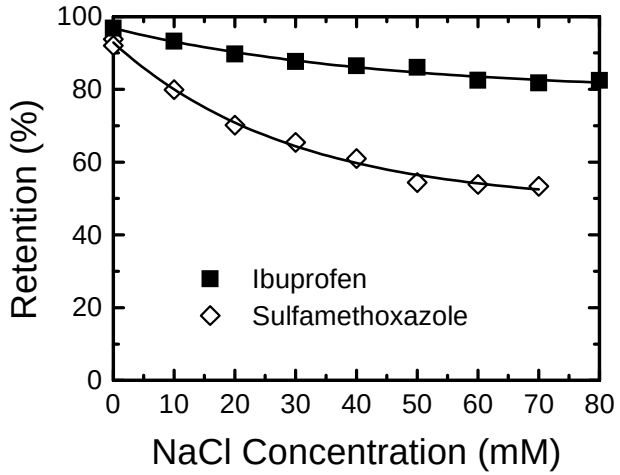

Figure 6

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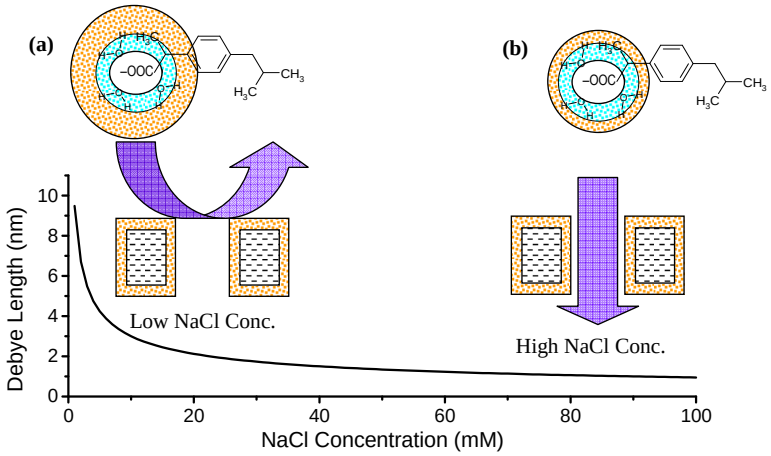

Figure 7

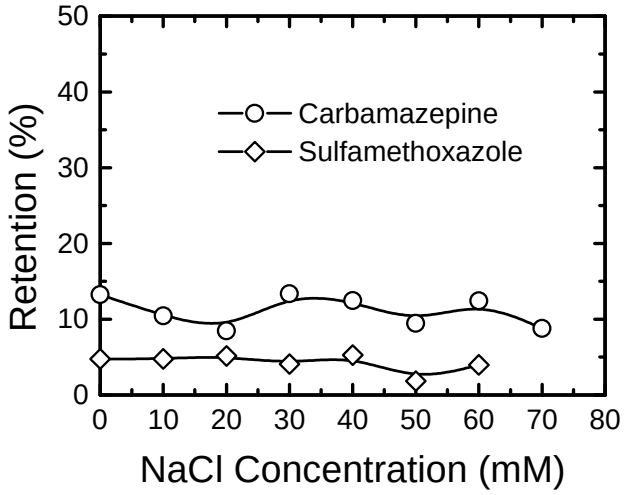

Figure 8

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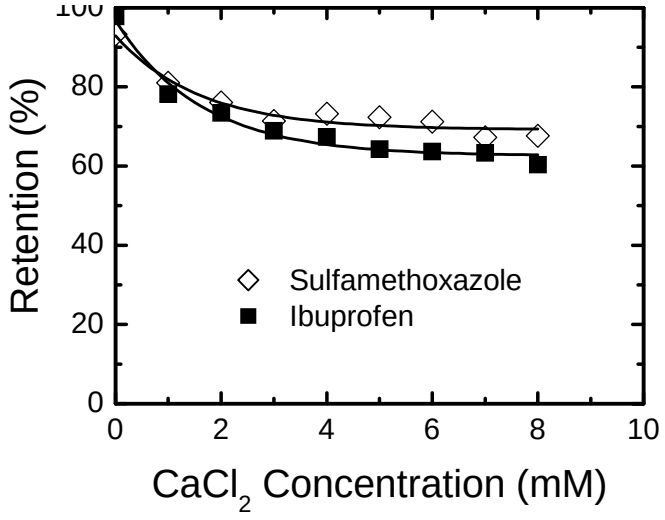

Figure 9